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Investigation of the Effect of Al_2O_3 Nanoparticle-Added MQL Lubricant on Sustainable and Clean Manufacturing

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Abstract: In this study, in order to improve the characteristics of the vegetable-based cutting fluids used in the MQL technique and increase the machining performance of MQL and its positive effects on sustainable manufacturing, the effects of the MQL method with nano-Al_2O_3 additives on surface roughness (Ra) and cutting temperature (Ctt) were examined through turning experiments carried out by adding nano-Al_2O_3 to the vegetable-based cutting fluid. For this purpose, machining tests were carried out on hot work tool steel alloyed with Cr-Ni-Mo that has a delivery hardness of 45 HRC. In hard machining experiments, three techniques for cooling and lubricating (dry cutting, MQL, and nano-MQL), three cutting speeds (V) (100, 130, 160 m/min), three feed rates (f) (0.10, 0.125, and 0.15 mm/rev), and two different ceramic cutting tools (uncoated and TiN-coated with PVD methods) were used as control factors. For Ra, the nano-MQL method provided an average of 21.49% improvement compared to other cooling methods. For Ctt, this rate increased to 26.7%. In crater wear areas, the nano-MQL method again exhibited the lowest wear values, decreasing performance by approximately 50%. The results of this research showed that the tests conducted using the cooling of nano-MQL approach produced the best results for all output metrics (Ra, Ctt, and crater wear).

Keywords: Cr-Ni-Mo alloyed steel; sustainable and clean manufacturing; minimum quantity lubrication; nano-Al_2O_3; cutting temperature; surface roughness

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1. Introduction

The process of machining involves removing material from the workpiece using the help of power and tools to bring the materials to the desired shape and size. The competition between the companies that use machining methods has also increased the demand for high efficiency. Efficient production is achieved by reducing production costs, maintaining or improving product quality quickly, and increasing the number of products produced. The cutting speed used in machining methods is an essential factor for efficient production. The acceleration of the cutting speed also raises the quantity of products produced in a short amount of time [1]. However, high cutting speeds create high cutting temperatures. These high cutting temperatures lead to negative effects such as inadequate surface quality, excessive tool wear, low dimensional stability, and short tool life [2].

In machining methods, the traditional cutting fluid cooling/lubrication method is mainly used to reduce these elevated temperatures within the cutting area. However, the application of these cutting fluids has both advantages and disadvantages in the manufacturing process. Cutting fluids containing chemical components harm human health by coming into contact with workers' skin in the production line and harms nature by mixing with the soil in cases where waste management is not conducted well [3]. In addition, there is an increase in operating costs due to the storage, disposal, and supply of these cutting fluids in relation to the total production cost [4,5]. Therefore, the increasing costs of cutting fluids, their environmental pollution, and their negative effects on human health have led to the development of new lubrication techniques such as the minimum quantity lubrication (MQL) system instead of traditional cutting fluid cooling/lubrication methods [6,7]. The MQL method is a lubricating and cooling technique where a tiny quantity of cutting fluid is misted onto the area being sliced where the workpiece and the tool interact with pressurized air's assistance [8]. Thus, the application of a tiny quantity of cutting fluid in the MQL method has features that increase positive effects on operational efficiency and sustainable manufacturing, such as reducing operating costs compared to the conventional cooling/lubrication method, being harmless to human health, and eliminating the waste cost of end-of-life oils [9]. Today, many researchers obtain nanofluids by adding additives, also known as nanoparticles, to the MQL technique's cutting fluid. Thanks to these nanofluids, the friction between the cutting tool and the workpiece can be significantly decreased, and lower cutting temperatures can be achieved by increasing the thermal conductivity of the cutting fluid. Thus, better cutting tool life and surface quality can be achieved with reduced cutting temperature and friction coefficient [10].

Lacelle et al. [11] examined the impact of spraying cutting fluids in high speed milling through experimentation and numerical analysis. After 150 m of cutting distance, flank wear was measured as around 0.16 mm with conventional coolant, while flank wear value decreased to 0.1 mm with the MQL method. As a result, the MQL method provided approximately 40 percent reduction in tool wear [11]. Al_2O_3/MoS_2 hybrid nanofluid MQL's effects on surface roughness, cutting force, tool wear, and tool life in hard turning were examined by Ngoc et al. [12]. Hard machining differs from normal cutting in that the wear modes are mechanical scratching and chipping, and the wear lands on the rake and flank faces are concentrated on the main cutting edge. It was shown that the cooling lubrication state has an impact on tool wear as well as on cutting parameters. Additionally, compared to dry and Al_2O_3 nanofluid MQL conditions, the cooling and lubricating efficacy of the Al_2O_3/MoS_2 hybrid nanofluid MQL condition resulted in improved machined surface roughness and longer tool life [12].

Turning experiments were conducted in this study by adding 0.5% nano-Al_2O_3 by weight into the vegetable-based cutting fluid used in the MQL technique in order to reduce the cutting temperature by increasing the liquid mixture's thermal conductivity. Thanks to the nano-Al_2O_3 nanoparticles added to the vegetable-based cutting fluid, the lubrication property of the cutting fluid was improved by increasing the viscosity to the optimum level, thus enhancing the surface quality and lessening surface roughness due to its polishing property [13]. Turning experiments were carried out according to the experimental design using three different cooling/lubrication methods (dry cutting, MQL, and nano-MQL), three different cutting speeds (100, 130, and 160 m/min), three different feed rates (0.10, 0.125, and 0.15 mm/rev), and two different cutting tools (the PVD method of Al_2O_3 + TiC matrix-based and TiN-coated ceramic tool (AB2010) and the Al_2O_3 + TiC matrix-based uncoated mixed alumina ceramic tool (AB30)) on a universal lathe. In turning experiments, the effects of nano-Al_2O_3 addition on surface roughness (Ra) and cutting temperature (Ctt) were examined, and the most optimum experimental parameters among the control factors were determined. Additionally, an analysis of variance (ANOVA) was conducted at a 95% confidence level to establish the influence levels of the control parameters on cutting temperature (Ctt) and surface roughness (Ra).

2. Material and Methods

In this study, hot work tool steel alloyed with Cr, Ni, and Mo, which is widely used in extrusion, hot forging, forming dies and hot cutting blades, was used as a test sample. The hot work tool steel alloyed with Cr, Ni, and Mo we used was Ø60 $\times$ 300 mm in size, and its delivery hardness was around 45 HRC. Cr-Ni-Mo-alloyed hot work tool steel measuring 300 mm in length and 60 mm in diameter was used in the hard machining experiments. Table 1 provides the workpiece's chemical composition.

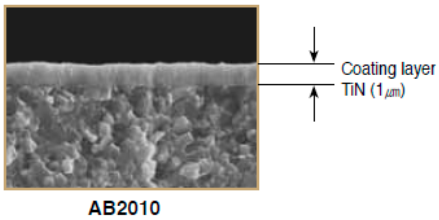
Table 1. Chemical composition (%) of test samples.

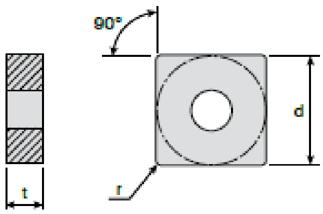
C	Mn	P	S	Si	Cr	Mo	Ni
0.65–0.75	0.25–0.80	0.03	0.03	0.10–0.50	0.60–1.20	0.50	1.25–2.00

In the hard turning experiments, cutting tools made of uncoated mixed alumina ceramic based on an Al_2O_3 + TiC matrix with code SNGA 120408 AB30 manufactured by TaeguTec cutting tool company, which has a widespread use in the industry, and ceramic cutting tools based on an Al_2O_3 + TiC matrix and coated with TiN by the PVD method with code SNGA 120408 AB2010, manufactured by the same company were used. The grade properties of the cutting tools are given in Table 2 [14]. PSBNR 2525M-12 external diameter cutting tools were connected using a rotating tool holder. A cutting tool that had not been used before was used for each experiment. The STN-40 model produced by Werte was used as the MQL system. The MQL system was potentiometer controlled, the cutting zone used a vegetable-based cutting fluid at a constant pressure and flow rate, and the nozzle was positioned 15 mm from the cutting tool tip.

Table 2. Coated and uncoated ceramic grade properties [14].

Grade	AB2010	AB30
Composition	Al_2O_3-TiCN	Al_2O_3-TiCN
Hardness (HRa)	94.5–95.0	94.5–95.0
Toughness (KIC)	3.0–3.5	3.2–3.7
Coating Layer	TiN	Uncoated





In this study, Oelheld DiaCut EMM 2500 vegetable-based cutting fluid, which is 100% biodegradable and has technical specifications that are listed in Table 3, was used because it does not leave any residue behind and is also suitable for worker health. The process of making the cutting fluid from vegetables for the nano-MQL method was carried out in 2 steps. In the first step, nano-Al_2O_3 nanoparticles, whose technical specifications, size, and chemical composition are given in Table 4, were added to the cutting fluid by weighing it with a precision balance at a rate of 0.5% by weight. In order to ensure homogeneous distribution of nano-Al_2O_3 nanoparticles added to the cutting fluid in the second step, the nano-Al_2O_3-reinforced cutting fluid for the nano-MQL technique was made by mixing it with a Heidolph Hei-Torque mechanical stirrer at 600 rpm for 30 min, a Bandelin SonoPuls HD3200 ultrasonic homogenizer at 100 W for 30 min, and a Heidolph MR Hei-Tec magnetic stirrer at 700 rpm for 30 min, respectively. The steps for the preparation of the nanofluid are shown in Figure 1.

Table 3. Oelheld DiaCut EMM 2500 vegetable-based cutting fluid characteristics.

Density + 15 °C (g/cm^3)	0.90
Kinematic Viscosity + 40 °C (cSt)	25.5
Flash Point (°C)	>200
Oil Type	Vegetable

Table 4. Nano-Al_2O_3 technical specifications, size, and chemical composition.

Technical Specifications	Size	Chemical Composition (wt. %)	
Gamma, Purity (%) 99.5+	99.5+	SiO_2	max. 0.015
Color	White	Fe_2O_3	max. 0.020
Average Particle Size (nm) 18	18	Na_2O	max. 0.450
Specific Surface Area (m^2/gr) 140	140	CaO	max. 0.050
Specific Heat Capacity (J/kg.K) 890	890	P_2O_5	max. 0.0012
Density (kg/m^3) 3900	3900	K_2O	max. 0.018
Morphology	Spherical	ZnO	max. 0.0015
Particle shape	Hydrophilic	TiO_2	max. 0.0025

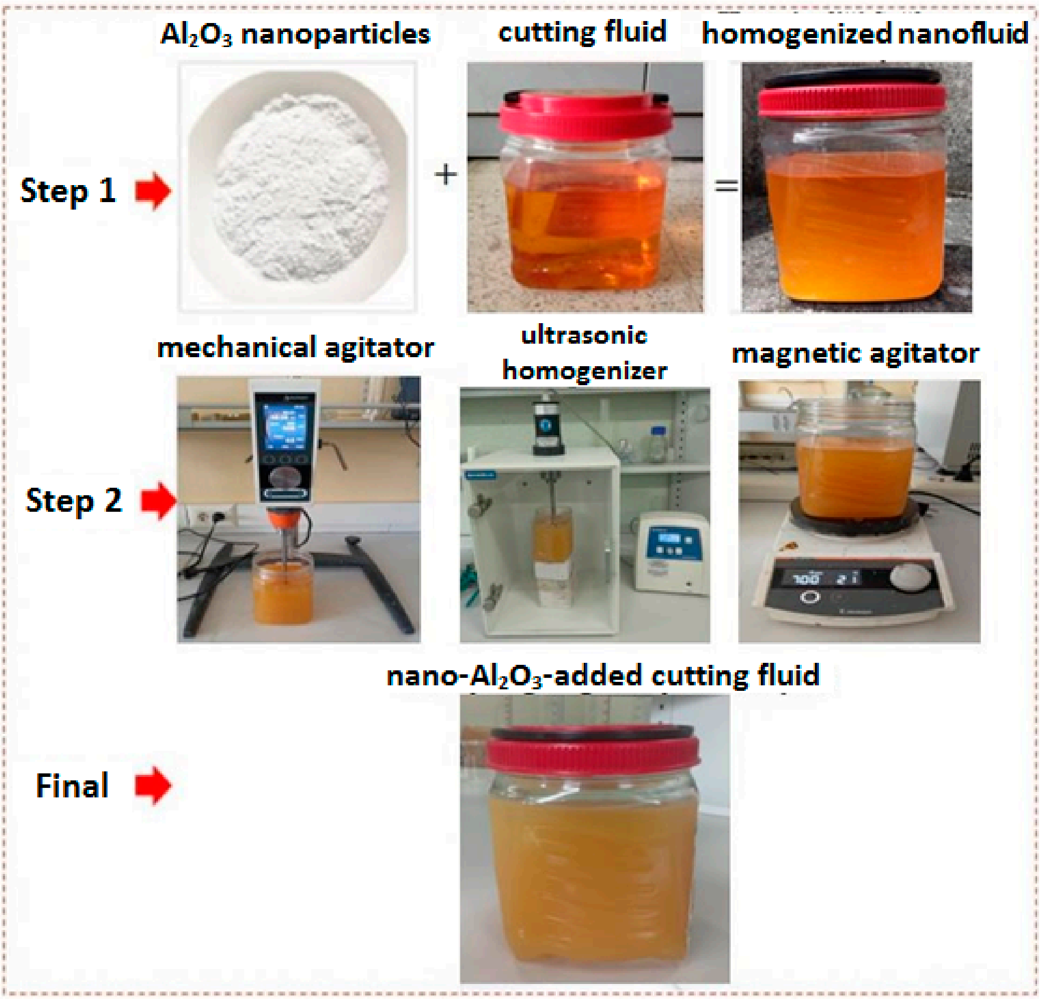


Figure 1. Steps applied in the preparation of vegetable-based nanofluid.

Since the Al_2O_3 nanoparticles included into the cutting fluid made of vegetables will change the viscosity value of the vegetable-based cutting fluid due to their technical properties [13]. The cutting fluids' kinematic viscosity values were measured with a Fungilab EXPERT brand viscometer. In this investigation, to ascertain the effect of 0.5% nano-Al_2O_3 nanoparticle addition to the cutting fluid made from vegetables in the turning of hot work tool steel alloyed with Cr, Ni, and Mo on the MQL method and the optimum experimental parameters in the turning of Cr-Ni-Mo alloyed steel, the cooling/lubrication method, the cutting tool, feed rate, and cutting speed were chosen as the control variables. The cutting parameter (feed rate, cutting speed) data were determined by taking into account the manufacturer's suggestions for cutting tools and the preliminary experiments, and the chip removal process was completed at a steady cutting depth (0.5 mm) in the turning experiments. Three iterations of each experiment were conducted. The surface roughness and cutting temperature values were found by taking the average of these three experiments. Information showing the levels and the control factors of the control factors is given in Table 5. During each experiment, the highest cutting temperature (Ctt) was examined, the workpiece's surface roughness (Ra) was measured, and the data obtained after each experiment was recorded. Tool wear experiments were carried out by hard turning Cr-Ni-Mo alloy hot work tool steel, uncoated and coated ceramic tools at 100 m/min cutting speed, 0.1 mm/rev feed rate and 0.5 mm depth of cut for 15 min of machining time. In order to assess crater wear, SEM images were moved to the CAD environment at a 1:1 scale, crater areas were drawn precisely, and their areas were calculated.

Table 5. Hard machining parameters and levels.

Control Factors	Level 1	Level 2	Level 3
cooling/lubrication method	dry	MQL	Nano-MQL
cutting speed, V (m/min)	100	130	160
feed rate, f (mm/rev)	0.10	0.125	0.15
cutting tool type	AB2010	AB30	-

An OPTRIS brand PI 450 thermal camera (Optris Company, Berlin, Germany) was used in turning tests to measure temperature data that occurred in the cutting zone on the cutting tool. In order to determine the surface quality of the workpiece as a result of the experiments, after each experiment, the measurement of surface roughness was completed by taking the surface roughness (Ra) arithmetic average from three distinct locations using the Mahr MarSurf PS10 brand surface roughness device (Mahr Group, Stuttgart, Germany). To determine the difference between cutting tools and cooling methods, 3D surface topographies were extracted with a Phase View optical profilometer (PhaseView Company, Paris, France). The experimental setup showing the equipment used in hard turning experiments and the created system is given in Figure 2.

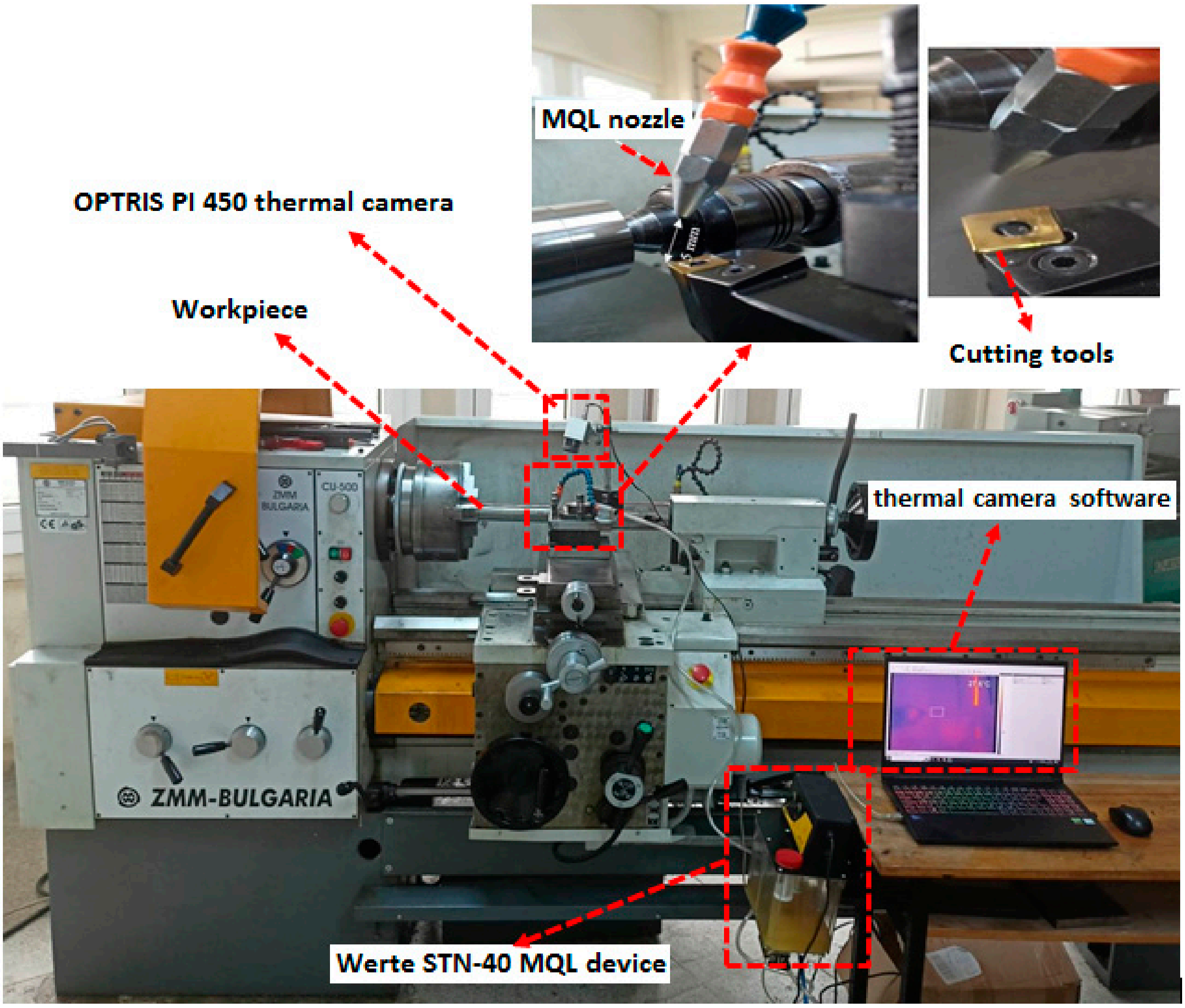


Figure 2. Experimental setup.

3. Discussion and Results

3.1. Evaluation of Surface Roughness Results

Three different cooling/lubrication techniques (dry cutting, MQL, and nano-MQL), three different cutting speeds (100, 130, and 160 m/min), three different feed rates (0.10, 0.125, and 0.15 mm/rev), and two different cutting tools (Al_2O_3 + TiC matrix-based uncoated mixed alumina ceramic tool (AB30) and Al_2O_3 + TiC matrix-based and TiN-coated ceramic (AB2010) by PVD method tool) were used in 54 turning experiments conducted on Cr-Ni-Mo alloyed steel. The values of surface roughness (Ra) derived from the experiments and the cutting fluid viscosity information used in MQL and nano-MQL cooling/lubrication methods are shown with the help of graphics in Figures 3–9. The surface roughness (Ra) values obtained from 54 experiments measured between 0.5083–1.0413 µm.

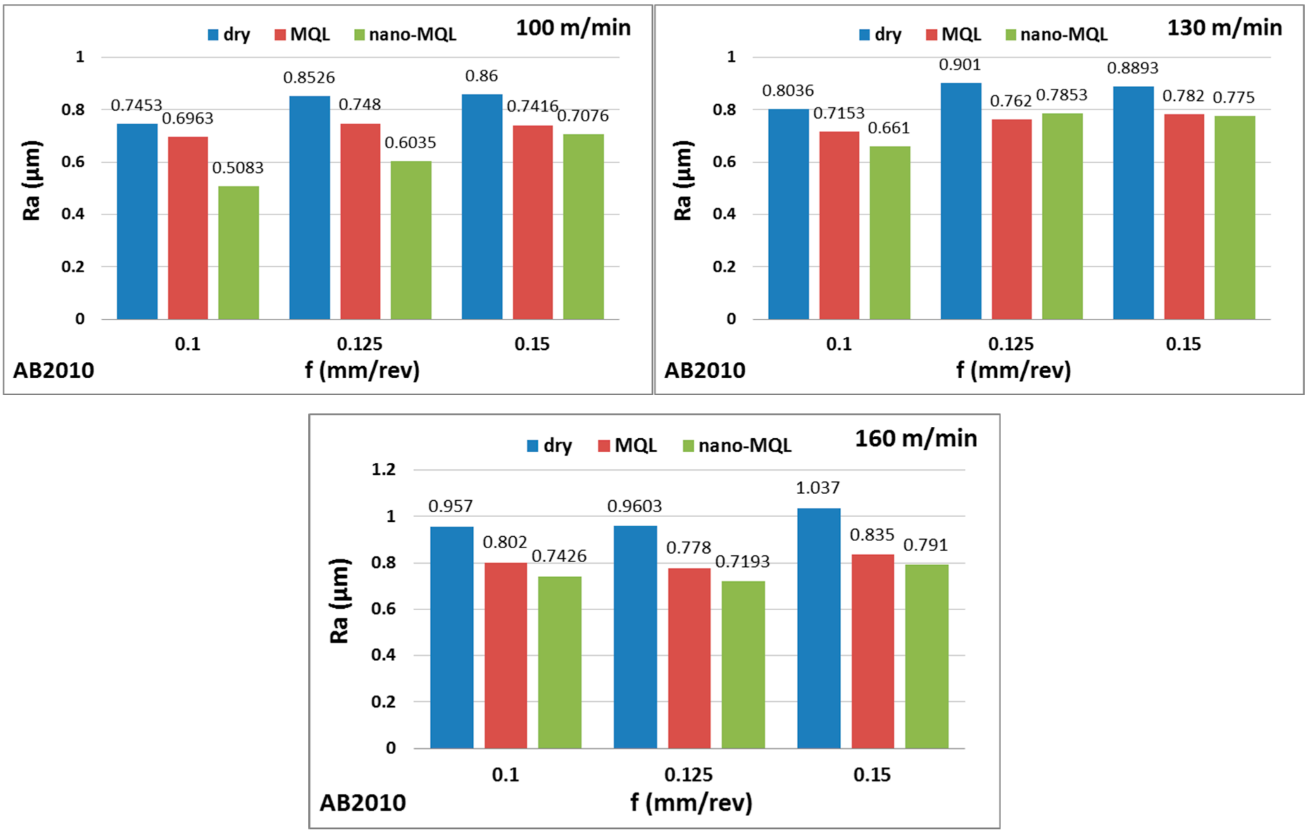


Figure 3. Ra results for AB2010 coated ceramic cutting tool.

As shown in the graph in Figure 3, for the 27 experiments performed with the AB2010-coded TiN-coated ceramic cutting tool, the surface roughness (Ra) values were between 0.5083–1.037 µm. In these experiments, performed with the AB2010-coded TiN-coated ceramic cutting tool, the lowest surface roughness (Ra) value of 0.5083 µm was obtained with the following parameters: 0.10 mm/rev lowest feed rate using the nano-MQL cooling/lubrication method and 100 m/min lowest cutting speed. Using dry cutting as the cooling/lubrication method, the greatest cutting speed parameters of 160 m/min and the highest feed rate of 0.15 mm/rev produced the highest surface roughness value of 1.037 µm. Again, when the graphs obtained from the experiments carried out with the AB2010-coded cutting tool were analyzed, it was found that surface roughness values often rise with an increase in feed rate when the cutting speed and cooling/lubrication technique are constantly maintained. The reason for this is high heat generation, because the cutting forces between the cutting tool and the workpiece rise as the feed rate increases, increasing the chip removal rate, and resulting in an increase in surface roughness [15]. Therefore, in this study, the optimum feed rate for the TiN-coated ceramic cutting AB2010-coded tool to have a low surface roughness (Ra) value, i.e., better surface quality, was found to be 0.10 mm/rev. Again, when the experimental graphs performed with the AB2010-coded cutting tool are examined, the surface roughness values obtained were found to be due to different cutting speeds, while the feed rate and cooling/lubrication method even when. As may be observed, the surface roughness values often rise in tandem with an increase in cutting speed. Up to a certain extent, surface roughness diminishes as cutting speed increases because cutting forces decrease as cutting speed increases. Here, the reduction in cutting force as the cutting speed increases is due to both the decrease in the contact area of the cutting tool on the rake surface and the decrease in the yield zone strength formed on the rake surface. However, after a certain cutting speed, the cutting force continuously increases as the cutting speed increases, and the amount of cutting tool wear increases with the increasing cutting force [16]. Here, the cutting procedure becomes less effective with the increased wear of the cutting tool and more roughness occurs on the surface [17,18]. Therefore, an optimum balance is required in the selection of cutting speed. In the experiments performed with the AB2010-coded cutting tool in this study, the optimum cutting speed was found to be 100 m/min. In the turning experiments carried out using the Nano-MQL method and AB2010 coded cutting tool, the values for surface roughness (Ra) were measured between 0.5083–0.791 µm. In the turning experiments carried out using the MQL method and the AB2010-coded cutting tool, the values for surface roughness (Ra) were measured between 0.6963–0.835 µm. In the turning experiments carried out using the dry method and the AB2010-coded cutting tool, the values for surface roughness (Ra) were measured between 0.7453–1.037 µm.

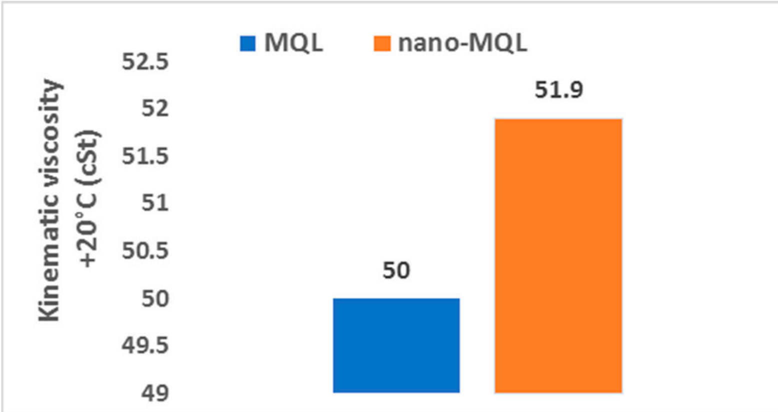


Figure 4. Kinematic viscosity values of cutting fluids used in MQL and nano-MQL methods.

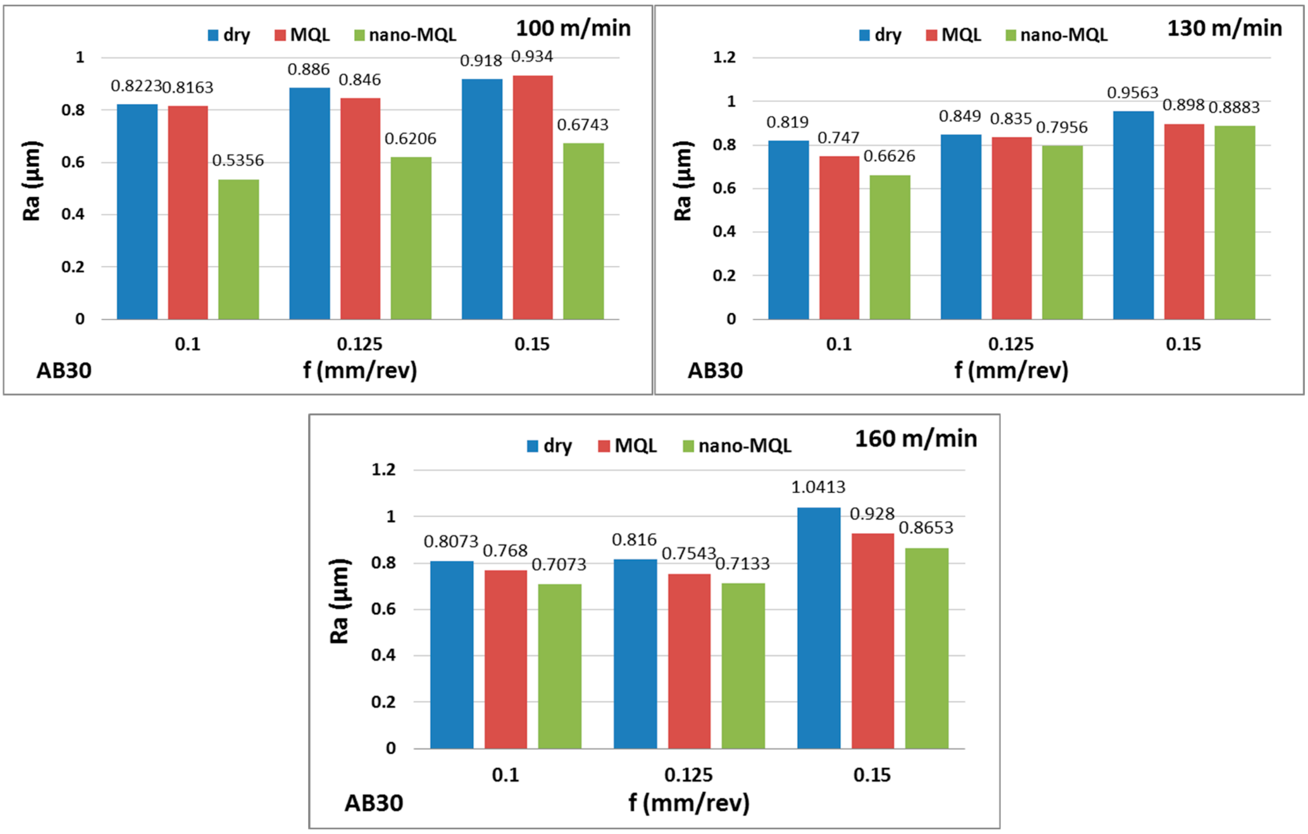


Figure 5. Ra results for AB30 uncoated ceramic cutting tool.

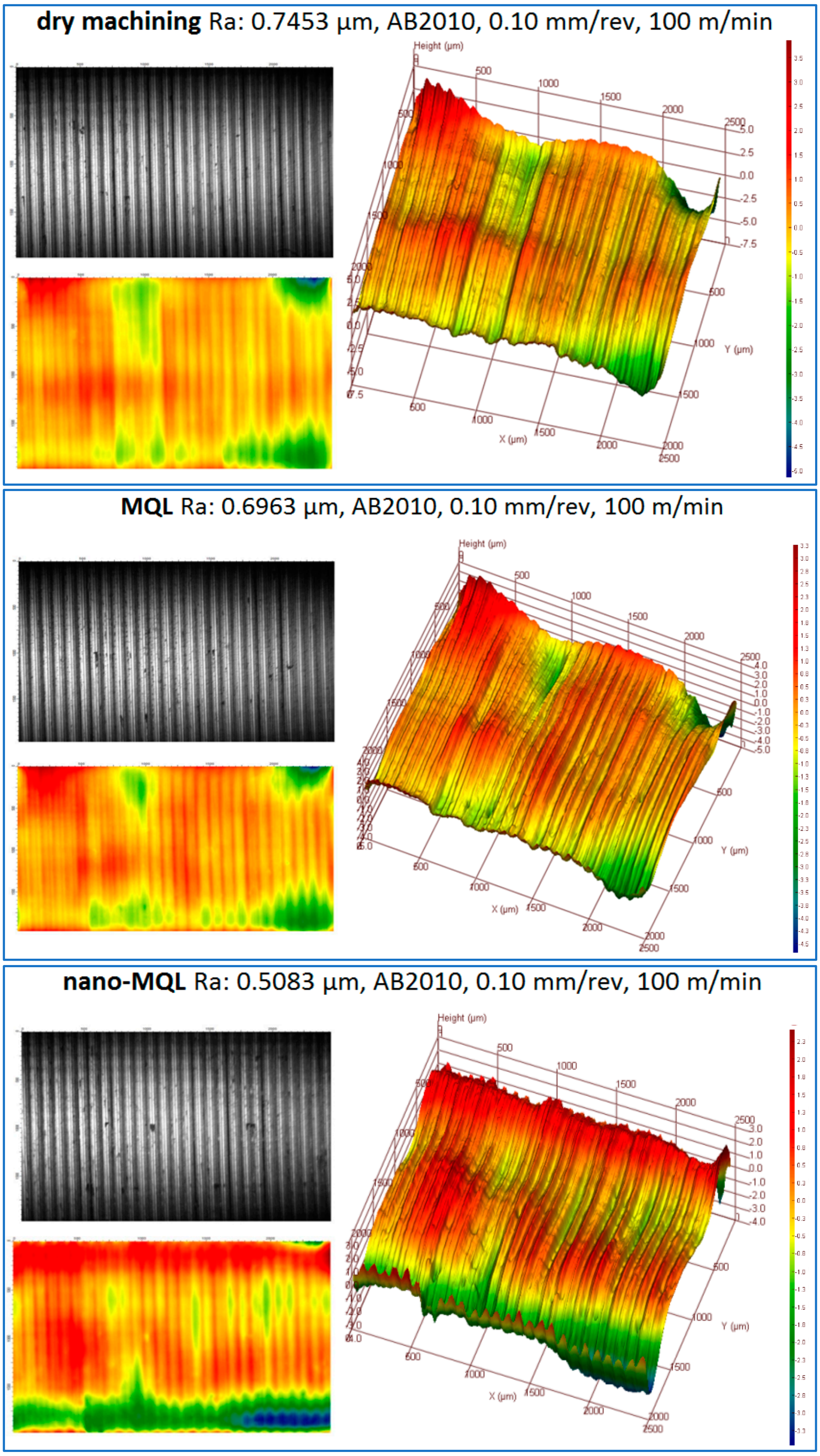


Figure 6. Pictures of machined surfaces' surface topography (AB2010).

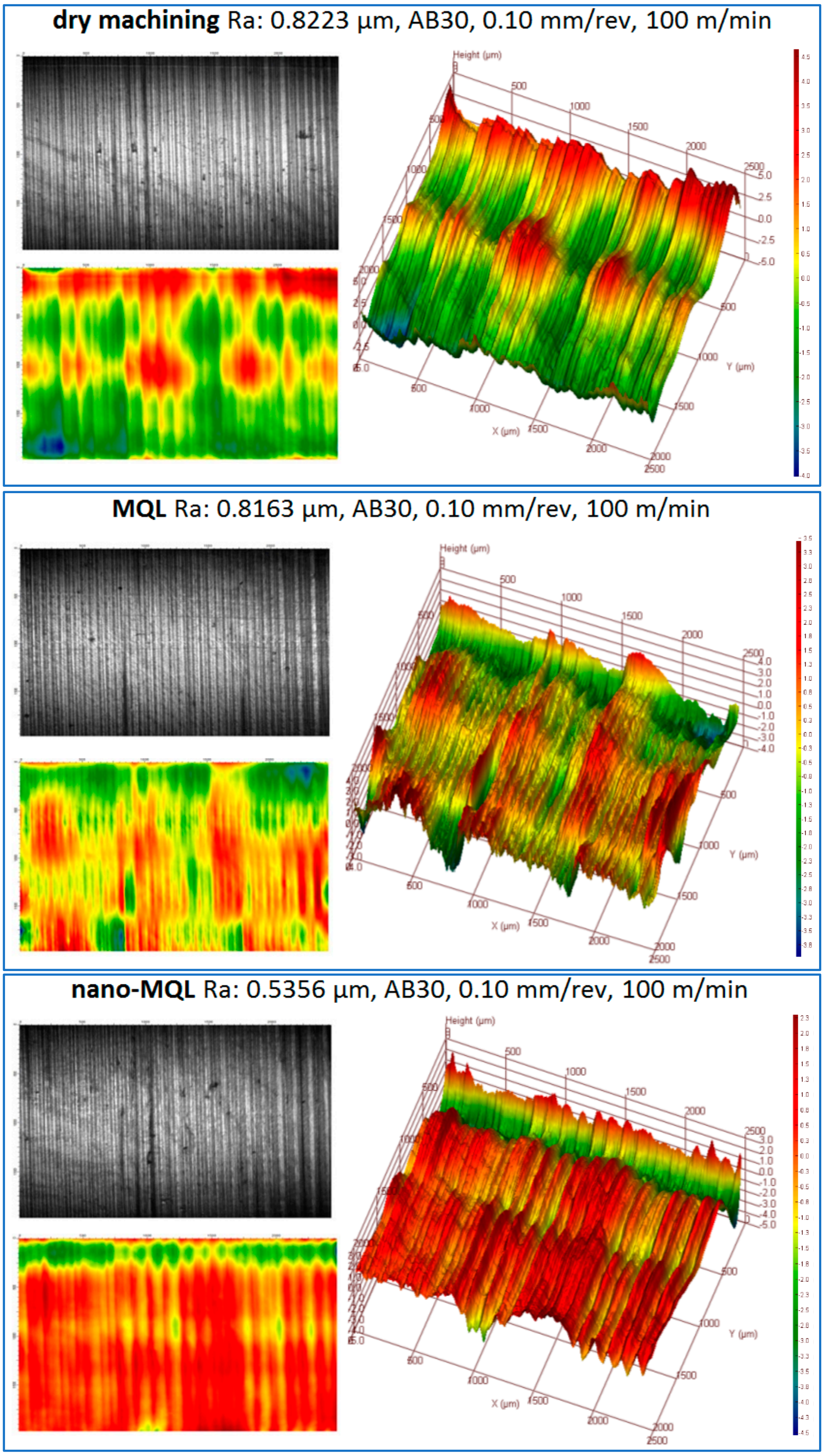


Figure 7. Pictures of machined surfaces' surface topography (AB30).

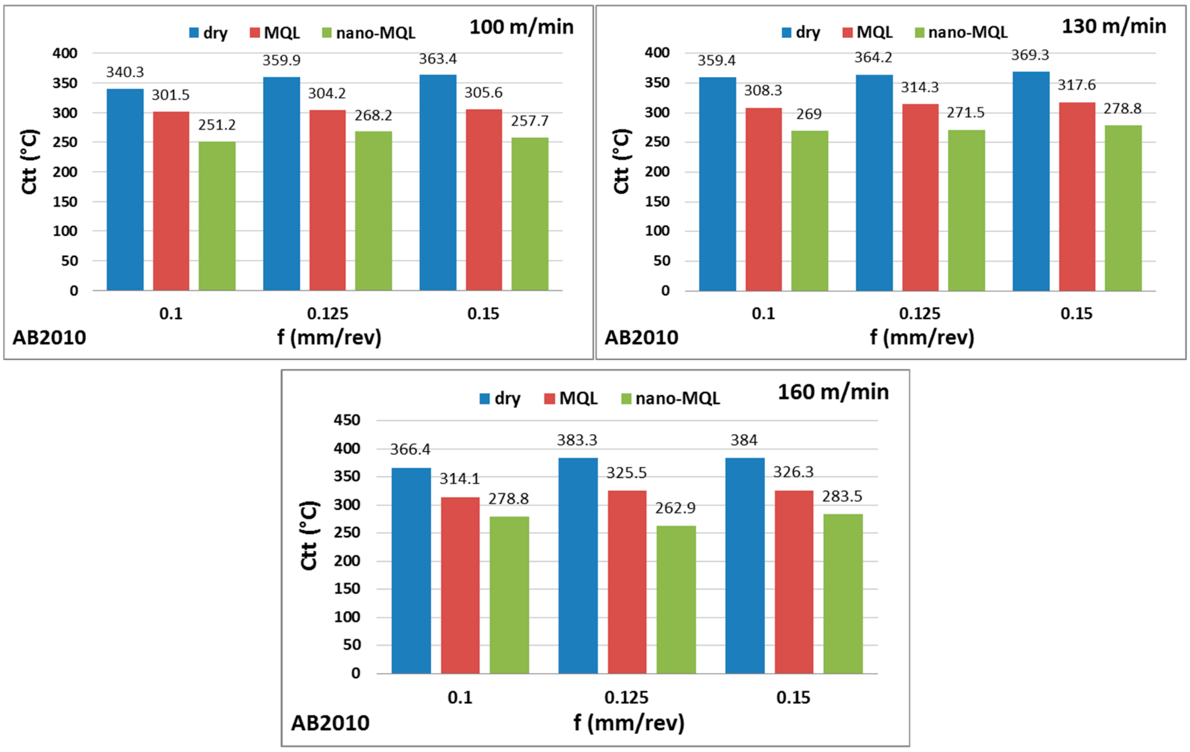


Figure 8. Cutting temperature results for AB2010 coated ceramic cutting tool.

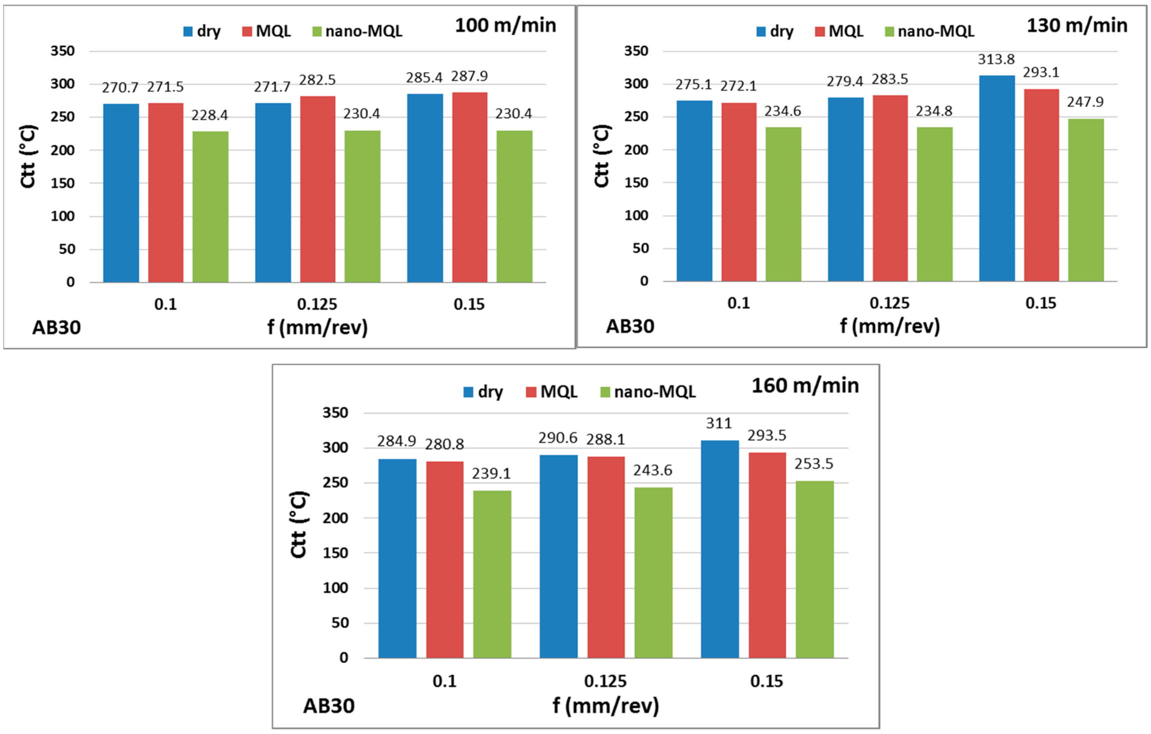


Figure 9. Cutting temperature results for AB30 uncoated ceramic cutting tool.

In Table 6, the Ra improvement rates of the cooling methods for AB2010 coated ceramic tools are given. Examining Table 6, it can be observed that an average of 13.97% and a maximum of 19.48% improvement was achieved with the MQL method in contrast to dry machining. However, an average of 8.51% and 21.49%, and a maximum of 27% and 31.8% improvement was achieved in surface roughness in the nano-MQL method using the ceramic cutting tool AB2010 in contrast to the MQL and dry methods, respectively. Because nanofluids have improved thermal properties, such as better thermal conductivity and heat transfer coefficients, in comparison to plain MQL, it was also observed that MQL + Al_2O_3 nanoparticles further reduce surface roughness [12]. Nanoparticle filling and finishing with superior anti-friction properties may be responsible for the enhanced surface quality achieved with the nanofluid MQL approach [13]. When we examine the graphs and improvement rates of the data acquired as a consequence of the tests conducted using the AB2010-coded cutting tool, we can say that the best technique of cooling and lubricating for the lowest surface roughness (Ra) is the nano-MQL method. The nano-MQL method is followed by the MQL and dry methods, respectively. The reason for this is that since there is no friction or temperature-reducing factors in the dry cutting method, elevated temperatures for cutting and high cutting forces are seen during the cutting process, and these negative factors bring negativities such as high cutting tool wear, creating increased surface roughness compared to the MQL and nano-MQL methods. Using the MQL approach, the compressed air has a cooling function, and the cutting fluid lowers friction in this area by acting as a lubricant between the cutting tool and the workpiece, and as a result, it provides the opportunity to obtain improved quality of the surface by creating lower cutting temperatures and lower cutting tool wear compared to the dry method [19]. In the nano-MQL method, the cutting temperatures are decreased by raising the cutting fluid's thermal conductivity with the Al_2O_3 nanoparticles added to the vegetable-based cutting fluid used in the MQL method. The viscosity is increased to the optimum level, as indicated in Figure 4, improving the lubrication properties of the cutting fluid. Thus, the surface roughness obtained in the nano-MQL method has superior surface quality in contrast to the MQL technique [19,20].

Table 6. Ra improvement rates of the cooling methods for AB2010 coated ceramic tool (%).

Cutting Tools	Feed Rate, f (mm/rev)	Cutting Speed, V (m/min)	Ra Improvement Rate of MQL Compared to dry	Ra Improvement Rate of Nano-MQL Compared to Dry	Ra Improvement Rate of Nano-MQL Compared to MQL
AB2010	0.1	100	6.57	31.80	27.00
		130	10.99	17.75	7.59
		160	16.20	22.40	7.41
	0.125	100	12.27	29.22	19.32
		130	15.43	12.84	−3.06
		160	18.98	25.10	7.54
	0.15	100	13.77	17.72	4.58
		130	12.07	12.85	0.90
		160	19.48	23.72	5.27
Average improvement (%)			13.97	21.49	8.51

Figure 5 shows the Ra results for the AB30-coded uncoated ceramic cutting tool. In the experiments conducted using the AB30-coded uncoated ceramic cutting tool, Ra values were measured between 0.5356–1.0413 µm. Using the nano-MQL cooling/lubrication approach, the lowest surface roughness (Ra) value of 0.5356 µm was achieved at the lowest feed rate of 0.10 mm/rev and the lowest cutting speed of 100 m/min using the AB30-coded uncoated ceramic cutting tool. Using the dry lubrication method as the cooling/lubrication method, the highest cutting speed of 160 m/min and the highest feed rate of 0.15 mm/rev resulted in the highest surface roughness value of 1.0413 µm. When the graphs for the AB30-coded cutting tool were examined, it was observed that the surface roughness values generally increased as the feed rate increased when the cutting speed and cooling/lubrication method were kept constant. Therefore, in this study, the optimum feed rate for the AB30-coded uncoated ceramic cutting tool was found to be 0.10 mm/rev for low surface roughness (Ra) value, i.e., better surface quality. Again, when the experimental graphs for the AB30-coded cutting tool were examined, when the feed rate and cooling/lubrication method were kept constant, and the surface roughness values obtained due to different cutting speeds were examined, it was seen that the surface roughness values generally increased as the cutting speed increased. In experiments were performed with the AB30-coded cutting tool, the optimum cutting speed for low surface roughness (Ra) value, i.e., high surface quality, was found to be 100 m/min.

In the turning experiments carried out using the nano-MQL method and the AB30-coded cutting tool, the Ra values were between 0.5356–0.8883 µm. In the turning tests conducted with the MQL method and the AB30-coded cutting tool, the Ra values were between 0.747–0.934 µm, and in the turning experiments carried out using the dry method and the AB30-coded cutting tool, the Ra values were between 0.8073–1.0413 µm. Table 7 shows the Ra improvement rates of the cooling methods for AB30 coated ceramic tools. When Table 7 is examined, an average of 14% and 18.42%, and a maximum of 34.39% and 34.87% improvement was achieved in surface roughness using the nano-MQL method with the AB30-coded ceramic cutting tool compared to the MQL and dry techniques, respectively. However, it was observed that an average of 4.82% and a maximum of 10.88% improvement was achieved using the MQL method compared to the dry method. When we examine the graphs and improvement rates of the data gathered from the tests using the AB30-coded uncoated ceramic cutting tool, we can say that the best lubrication method for the lowest Ra was the nano-MQL method, followed by the MQL and dry processing methods, respectively.

Table 7. Ra improvement rates of the cooling methods for AB30 uncoated ceramic tool (%).

Cutting Tools	Feed Rate, f (mm/rev)	Cutting Speed, V (m/min)	Ra Improvement Rate of MQL Compared to Dry	Ra Improvement Rate of Nano-MQL Compared to Dry	Ra Improvement Rate of Nano-MQL Compared to MQL
AB30	0.1	100	0.73	34.87	34.39
		130	8.79	19.10	11.30
		160	4.87	12.39	7.90
	0.125	100	4.51	29.95	26.64
		130	1.65	6.29	4.72
		160	7.56	12.59	5.44
	0.15	100	−1.74	26.55	27.81
		130	6.1	7.11	1.08
		160	10.88	16.90	6.76
Average improvement (%)			4.82	18.42	14.00

When comparing the AB2010-coded ceramic cutting TiN-coated tool using the PVD method and the AB30-coded ceramic cutting tool without coating in terms of Ra, the lowest surface roughness was obtained with the AB2010-coded ceramic cutting tool, at 0.5083 µm. Consequently, Ra was measured as 0.7837 µm with the AB2010-coded ceramic cutting tool, and in the tests conducted with the AB30-coded ceramic cutting tool, the average surface roughness was found to be 0.811 µm. With the AB2010-coded PVD method, 3.37% improved Ra values were acquired using the TiN-coated ceramic cutting tool compared with the AB30-coded uncoated ceramic cutting tool. This situation was attributed to the fact that the AB2010-coded ceramic cutting tool showed more wear resistance than the uncoated AB30-coded ceramic cutting tool thanks to its TiN coating, and as a result, lower Ra values were obtained [21].

When a general evaluation is made for Ra, the best surface quality was obtained in the MQL method (nano-MQL) with 0.5% Al_2O_3 reinforcement, followed by the MQL and dry-cutting methods, respectively. When we examined the cutting tools, the finest surface quality was obtained with the AB2010-coded Al_2O_3 + TiC matrix-based PVD method and TiN-coated ceramic cutting tool. When we examined the feed value and cutting speed, the lowest Ra value was obtained at 0.10 mm/rev feed rate and 100 m/min cutting speed. In total, the optimum experimental parameters that give the finest surface quality, i.e., the lowest surface roughness values, were obtained when the nano-MQL cooling/lubrication method, AB2010-coded cutting tool, 0.10 mm/rev feed rate, and 100 m/min cutting speed are used together. In order to better understand the effect of the cooling/lubrication method on Ra values, surface topography was obtained for the experiments in which different cooling/lubrication methods were used to keep the cutting speed, feed rate, and cutting tool parameters constant. When the surface topographic data given in Figures 6 and 7 were examined, it was seen that the peak and valley depths of the nano-MQL method were reduced in comparison to the MQL approach, and the MQL approach was reduced compared to the dry method.

The results of the variance analysis with a 95% confidence interval, performed in order to determine the magnitude of the effect of the factors that control cooling/lubrication method, cutting tool type, feed rate, and cutting speed on Ra, are presented in Table 8. While the F values indicate the effect level of each control factor, the contribution indicates the effect level of these control factors as a percentage. The control factor with the highest F value had the highest impact on the roughness of the surface.

Table 8. Surface roughness analysis of variance (ANOVA) results.

Control Factors	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution (%)
Cooling/ lubrication method	2	0.27831	0.27831	0.139153	40.26	0.000	42.85
Cutting speed, V (m/min)	2	0.06548	0.06548	0.032740	9.47	0.091	10.08
Feed rate, f (mm/rev)	2	0.13647	0.13647	0.068234	19.74	0.000	21.01
Cutting tool	1	0.01027	0.01027	0.010273	2.97	0.000	1.58
Error	46	0.15898	0.01446	0.003456			24.48
Total	53	0.64951					100.00

When the variance analysis given in Table 8 is examined, it can be determined that the most critical factor affecting surface roughness was the cooling/lubrication method, with an effect rate of 42.85%. The feed rate comes next, with an effect rate of 21.01%; the cutting speed, with an effect rate of 10.08%; and the cutting tool type, with an effect rate of 1.58%.

3.2. Evaluation of Cutting Temperature Results

During the machining process, high temperatures are generated due to friction between the workpiece and the cutting tool. These high temperatures affect the life and performance of the cutting tool and can cause problems such as wear, cracking, fracture, and deformation [22]. Heating caused by friction causes the cutting tool to fail to perform its function correctly and is a fundamental criterion in machinability evaluation. Therefore, during machining processes, it is crucial that the thermal properties of the cutting tool and the processed material are analyzed, as well as the temperature distribution between the workpiece and the cutting tool [23].

The cutting temperature values obtained due to hard machining are given in Figures 8 and 9. Cutting temperature values for all parameters were between 251.2 °C and 384 °C. The smallest Ra value with the AB2010-coded TiN-coated ceramic cutting tool was measured as 251.2 °C using the nano-MQL cooling/lubrication method, 0.10 mm/rev feed rate, and 100 m/min cutting speed. When the graphs for the AB2010-coded cutting tool were examined, it was observed that when the cutting speed and cooling/lubrication method were kept constant, the cutting temperature values generally grew with the rising feed rate. This can be explained as an increase in the friction between the workpiece and the cutting tool with the increase in feed rate [24]. Therefore, in this study, the optimum feed rate for the AB2010-coded TiN coated ceramic cutting tool, in regard to low cutting temperature value, was found to be 0.10 mm/rev. Again, when the experimental graphs for the AB2010-coded cutting tool were examined, when the feed rate and cooling/lubrication method were kept constant, and an analysis was conducted on the cutting temperature values and varying cutting speeds, the cutting temperature values generally increased as the cutting speed increased. The reason for this was the increase in cutting temperature due to the increased friction at both the feed rate and the cutting speed [25,26]. In this study, the optimum cutting speed was 100 m/min in the experiments conducted with the AB2010-coded cutting tool.

Table 9 displays a comparison of all cooling methods in relation to cutting temperature. Examining the table reveals that the cutting temperature improvement was achieved by an average of 14.04% and 26.37%, and a maximum of 19.23% and 31.41%, respectively, for the nano-MQL method with the AB2010-coded ceramic cutting tool in contrast to dry machining and MQL. With the MQL method, an average of 14.34% and a maximum of 15.91% improvement was achieved in contrast to dry machining. We can say that the best cooling/lubrication method for the lowest cutting temperature was the nano-MQL method, followed by the nano-MQL method and the dry method, respectively. This can be explained by the high friction caused by not using any liquid in the dry cutting method and the inadequate cooling due to the lack of compressed air, resulting in higher cutting temperatures compared to the MQL and nano-MQL methods. With the MQL method, the compressed air used provides cooling properties, and the vegetable-based cutting fluid has a lubricating property between the cutting tool and the workpiece, resulting in lower cutting temperatures. MQL + Al_2O_3 nanoparticles has a higher thermal conductivity and a higher convective heat transfer coefficient [12]. In the nano-MQL method, in addition to the compressed air used in the MQL method, the cutting fluid's thermal conductivity was increased when the Al_2O_3 nanoparticles were added, providing better cooling and improving the lubrication properties of the cutting fluid by increasing the viscosity to the optimum level. Thus, the cutting temperature obtained with the nano-MQL method was lower than that obtained with the MQL method [27,28].

Table 9. Ctt improvement rates of the cooling methods for AB2010 coated ceramic tool (%).

Cutting Tools	Feed Rate, f (mm/rev)	Cutting Speed, V (m/min)	Ra Improvement Rate of MQL Compared to Dry	Ra Improvement Rate of Nano-MQL Compared to Dry	Ra Improvement Rate of Nano-MQL Compared to MQL
AB2010	0.1	100	11.4	26.18	16.68
		130	14.22	25.15	12.75
		160	14.27	23.91	11.24
	0.125	100	15.48	25.48	11.83
		130	13.7	25.45	13.62
		160	15.08	31.41	19.23
	0.15	100	15.91	29.09	15.67
		130	14	24.51	12.47
		160	15.03	26.17	13.12
Average improvement (%)			14.34	26.37	14.34

Figure 9 shows that the cutting temperature values for the AB30-coded uncoated ceramic cutting tool were between 228.4 °C and 313.8 °C. The lowest cutting temperature value was 228.4 °C using the nano-MQL cooling/lubrication method, 100 m/min cutting speed, and 0.10 mm/rev feed rate, while the highest cutting temperature value was obtained with dry machining, 130 m/min cutting speed, and 0.15 mm/rev feed rate. It was noted that the cutting temperature values of the AB30 cutting tool, as in the AB20-coded cutting tool, generally increased with the increasing feed rate. In a similar vein, as cutting speed grew, so did cutting temperature values. At 100 m/min cutting speed and 0.10 mm/rev feed rate parameters, the lowest cutting temperature values for both cutting tools were recorded.

Table 10 displays the temperature at which cutting improvements occurred for the AB30-coded cutting tool under all cutting conditions. When Table 10 is examined, with the nano-MQL method, an average of 16.07% and 16.95% and a maximum of 19.97% and 21% improvement in cutting temperature was achieved, respectively, in contrast to the dry machining and MQL methods. An average of 1% and a maximum of 6.6% improvement was achieved with the MQL method in contrast to dry machining. We can say that the best cooling/lubrication method for obtaining the lowest cutting temperature value was the nano-MQL method, followed by the MQL and dry methods, respectively.

Table 10. Ctt improvement rates of the cooling methods for AB30 uncoated ceramic tool (%).

Cutting Tools	Feed Rate, f (mm/rev)	Cutting Speed, V (m/min)	Ra Improvement Rate of MQL Compared to Dry	Ra Improvement Rate of Nano-MQL Compared to Dry	Ra Improvement Rate of Nano-MQL Compared to MQL
AB30	0.1	100	−0.30	15.63	15.87
		130	1.09	14.72	13.78
		160	1.44	16.08	14.85
	0.125	100	−3.97	15.20	18.44
		130	−1.47	15.96	17.18
		160	0.86	16.17	15.45
	0.15	100	−0.88	19.27	19.97
		130	6.60	21.00	15.42
		160	5.63	18.49	13.63
Average improvement (%)			1.00	16.95	16.07

Among all the experimental results, the lowest Ctt value was measured as 228.4 °C with the AB2010-coded coated ceramic cutting tool. The cutting temperature values were measured as 315.897 °C and 269.6 °C for the tools coded AB2010 and AB30, respectively. The tool coded AB30 resulted in a 14.66% lower average cutting temperature compared to the AB2010-coded tool. The surface hardness was increased due to the coating applied to the cutting tools, and the wear resistance also increased [29]. Therefore, the AB2010-coded ceramic tool had higher cutting temperatures with the increased surface hardness with the TiN coating. However, although the 2010-coded TiN-coated ceramic cutting tool showed higher cutting temperatures than the AB30-coded uncoated ceramic cutting tool with the PVD method, the AB2010-coded ceramic cutting tool showed higher fracture resistance than the AB30-coded cutting tool, thanks to the TiN coating [30].

The results of the variance analysis at a 95% confidence interval performed to determine the magnitude of the effect of the factors that control, cooling/lubrication method, cutting tool type, feed rate, and cutting speed on Ctt are presented in Table 11. The table reveals that the most important factor affecting the cutting temperature was the cooling/lubrication method, with an effect rate of 53.51%. It was observed that the cooling/lubrication method was succeeded by the type of cutting tool, with an effect rate of

32.02%; the cutting speed, with an effect rate of 2.77%; and the feed rate, with an effect rate of 2.03%, respectively.

Table 11. Results of analysis of variance (ANOVA) for cutting temperature.

Control Factors	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution (%)
Cooling/ lubrication method	2	48,414	48,414	24,207.2	127.32	0.000	53.51
Cutting speed, V (m/min)	2	2509	2509	1254.5	6.60	0.003	2.77
Feed rate, f (mm/rev)	2	1837	1837	918.4	4.83	0.012	2.03
Cutting tool	1	28,977	28,977	28,976.9	152.41	0.000	32.02
Error	46	8746	8746	190.1			9.67
Total	53	90,483					100.00

3.3. Evaluation of Tool Wear (Crater Wear)

By computing the surface area of the craters in the CBT (Computer-Aided Design) environment, the crater wear values resulting from the turning process carried out at 100 m/min cutting speed, 0.1 mm/rev feed rate, and 0.5 mm cutting depth for 15 min were determined. Figures 10 and 11 show how crater wear varied according to the kind of cooling process and cutting tool. In terms of crater wear, the lowest wear values according to the cooling method were obtained with the nano-MQL method. The highest wear values were later found under dry machining circumstances, even though the MQL process produced the least amount of crater wear.

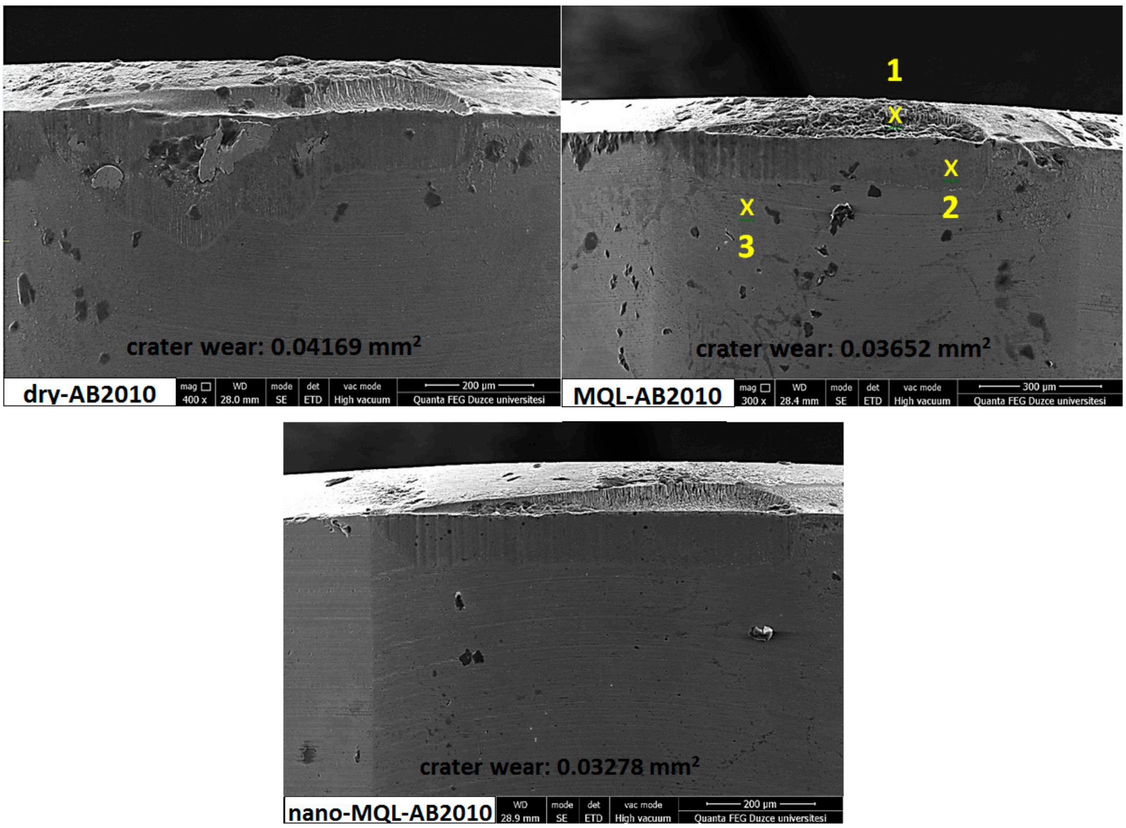


Figure 10. Crater wear changes depending on the cooling method used for AB2010.

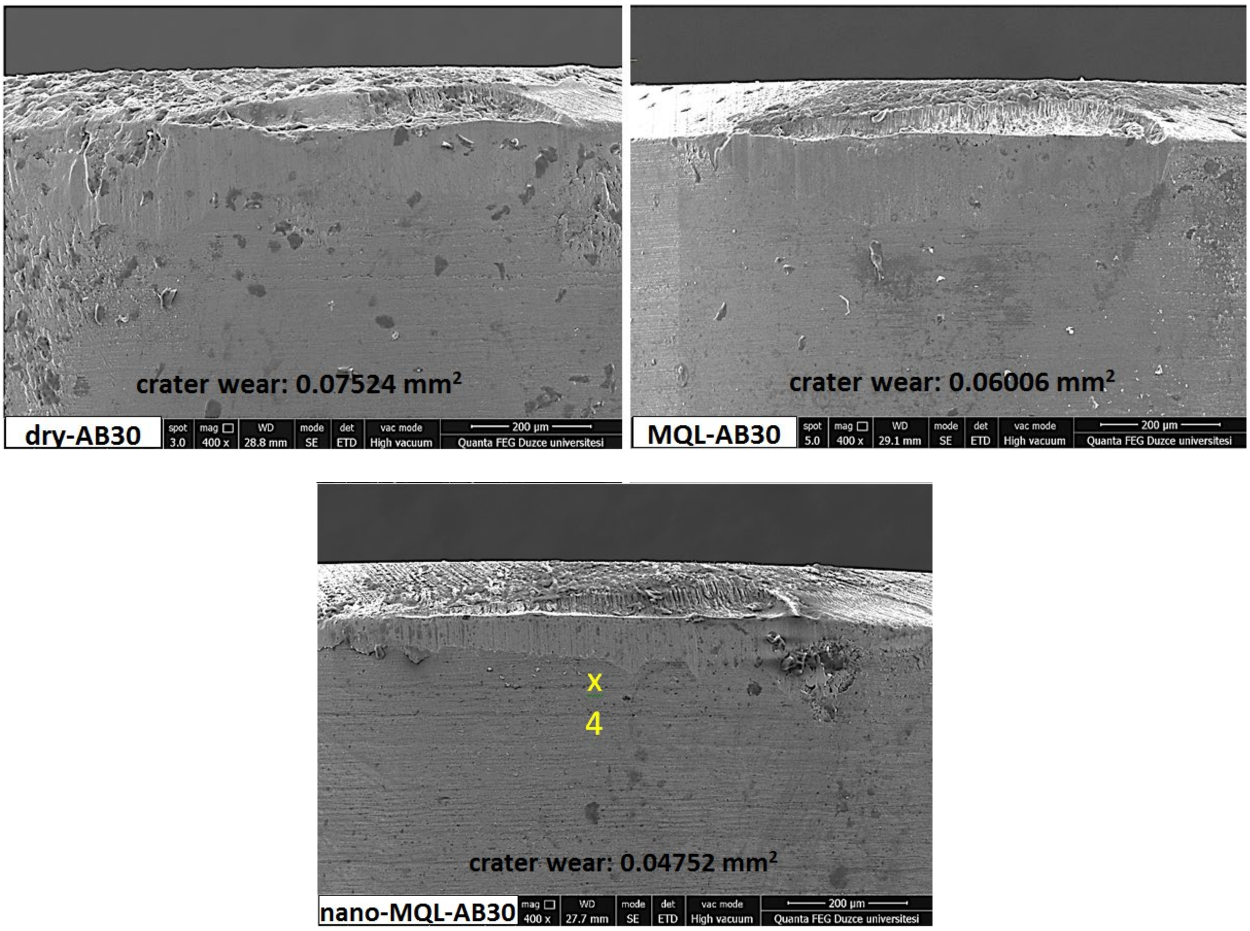


Figure 11. Crater wear changes depending on the cooling method for AB30.

According to this study, abrasion, adhesion, and adhesion-induced damage types including flank wear and BUE are some typical issues in the machining of Cr-Ni-Mo-alloyed hot work tool steel. The primary cause of abrasive wear has been identified as hard abrasive carbide particles present in Cr-Ni-Mo-alloyed hot work tool steel and tool particles that have been removed from the substrate.

High temperatures and strains induce the workpiece material to adhere to tool surfaces, which results in adhesion wear [31,32]. Adhesion can occasionally appear as a thin coating on the cutting tool. In other instances, as seen in Figures 10 and 11, it may show up on the tool edge in BUE form. According to Akhtar et al. [31], medium cutting speeds are the most likely to cause adhesion wear. Attrition wear, which indicates less adhesion, occurs when the temperature is insufficient for complete adhesion or welding.

In light of the literature, it is thought that the crater wear that may occur on the cutting tool surfaces exposed to friction during cutting under MQL and nano-MQL conditions will occur at lower rates. It was found that the crater wear values given in the figure vary between 0.03278 mm^2 and 0.07524 mm^2. With the nano-MQL method, the AB2010 coated cutting tool produced the lowest crater wear value of 0.03278 mm^2 after 15 min of machining. The lowest wear values for dry machining and MQL methods were calculated as 0.04169 mm^2 and 0.03652 mm^2, respectively. When the cutting tools were compared with each other, at the end of 15 min of machining time, the Al_2O_3 + TiC matrix-based and TiN-coated ceramic tool (AB2010) with PVD method provided 50% lower crater wear than the Al_2O_3+TiC matrix-based uncoated mixed alumina ceramic (AB30) tool. This result was associated with the TiN coating on the top layer of this cutting tool providing a low friction coefficient and good crater wear resistance despite not being a very hard material [33,34]. In general, tool life is not limited by minor crater wear. In fact, crater development makes the tool rake angle more effective, which lowers surface roughness. The cutting edge is weakened by excessive crater wear, though, and the tool may break or deform [34,35]. As a result, it degrades the quality of the machined surface, leading to wear types on the cutting tool's surface and edge areas, including flank wear and crater wear [36,37].

Figure 12 shows the EDX analysis results obtained from the cutting tools. Since the adhesion size was at the micro level, it may be said that the cooling/lubrication technique used helps avoid adhesion. In addition, the rough appearance of the worn areas in Figures 10 and 11 shows that abrasive and adhesive wear mechanisms were effective [38,39]. Tool particles were created and transported with the material flow as the workpiece material cycles between sticking and sliding on the cutting tool. The movement between the cutting tool and the chip, the operative cutting process, irregular depth of cut, and the vibration produce an irregular material flow that will trigger wear [40,41]. It is believed that severe mechanical loads also caused the coating material to peel, as seen on the rake face of the cutting inserts (Figures 10 and 11). Figures 10 and 11 show that there was a small amount of adhered workpiece material in the cutting tool zones, indicating that the cooling/lubrication methods applied with Al_2O_3 nanoparticle-added nanofluid-MQL are appropriate for hard turning of hot work tool steel alloyed with Cr, Ni, and Mo with ceramic cutting tools.

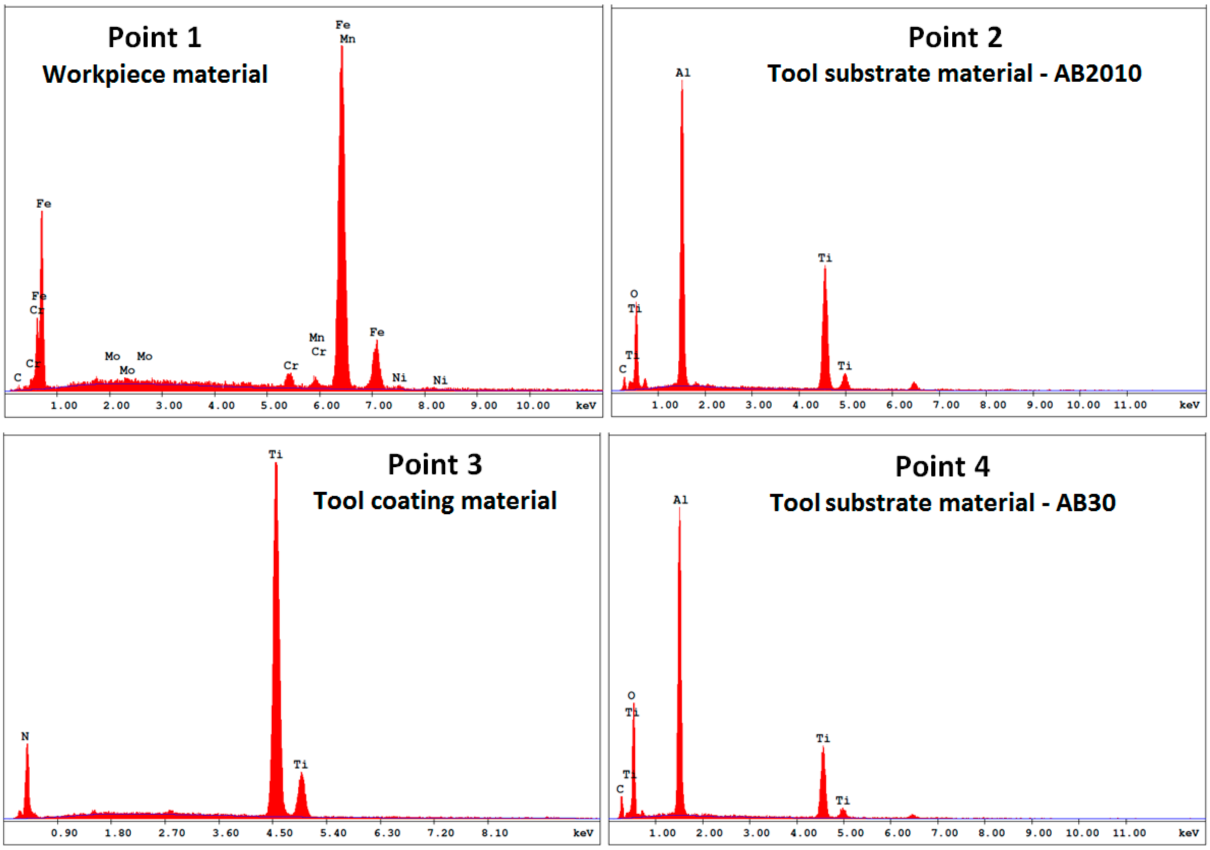


Figure 12. EDX analysis results for cutting tools.

4. Conclusions

In this study, the performance of the MQL and Al_2O_3-added MQL methods in the hard turning process was investigated in relation to dry cutting. In this context, surface roughness, cutting temperature, and tool wear experiments were carried out. The results obtained from this study are listed below.

1. Under the same experimental parameters using the cutting tool coded AB2010, an average of 8.51% and a maximum of 27% improvement was achieved for Ra in the

nano-MQL method compared to the MQL method, and an average of 21.49% and a maximum of 31.8% improvement was achieved in contrast with dry machining. In the MQL approach, an average of 13.97% and a maximum of 19.48% improvement was achieved in surface roughness compared to dry machining.

2. For the cutting tool coded AB30, an average of 14% and a maximum of 34.39% improvement was achieved for Ra in the nano-MQL method compared to the MQL method, and an average of 18.42% and a maximum of 34.87% improvement was achieved compared to dry machining. The MQL method achieved an average of 4.82% and a maximum of 10.88% improvement in surface roughness compared to dry machining.
3. Under the same experimental parameters using the cutting tool coded AB2010, an average of 14.04% and a maximum of 19.23% improvement was achieved for the cutting temperature in the nano-MQL method compared to the MQL method, and an average of 26.37% and a maximum of 31.41% improvement was achieved compared to dry machining. The MQL method achieved an average of 14.34% and a maximum of 15.91% temperature increase for cutting as opposed to dry machining.
4. For the uncoated ceramic tool coded AB30, an average of 16.07% and a maximum of 19.97% improvement was achieved in the nano-MQL method for cutting temperature compared to the MQL method, and an average of 16.95% and a maximum of 21% improvement was achieved compared to dry machining. The MQL method achieved an average of 1% and a maximum of 6.6% improvement in cutting temperature compared to dry machining.
5. Considering all cutting parameters, the lowest Ra values were achieved for both cutting tools when using the nano-MQL method, 0.10 mm/rev feed rate, and 100 m/min cutting speed parameters.
6. According to the ANOVA results, the most essential factors for Ra were found to be the cooling/lubrication method, with an effect rate of 42.85%, the feed rate, with an effect rate of 21.01%, the cutting speed, with an effect rate of 10.08%, and the cutting tool type, with an effect rate of 1.58%. For Ctt, it was determined that the cooling/lubrication method had an effect rate of 53.51%, cutting tool type had an effect rate of 32.02%, cutting speed had an effect rate of 2.77%, and feed rate had an effect rate of 2.03%.
7. At the end of 15 min of machining time, the Al_2O_3 + TiC matrix-based and TiN-coated ceramic tool (AB2010) with the PVD method provided 50% lower crater wear than the Al_2O_3+TiC matrix-based uncoated mixed alumina ceramic tool (AB30).

As a result, it was observed that adding 0.5 wt. nano-Al_2O_3 to the vegetable-based cutting fluid used in the MQL method provided significantly better results in terms of surface roughness and cutting temperature values. As a result of the improvements provided by the nano-MQL method compared to MQL and hard dry machining methods, the increased use of the nano-MQL method in machining methods will be more efficient in terms of sustainable manufacturing.

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References

1. Junankar, A.A.; Parate, S.R.; Dethe, P.K.; Dhote, N.R.; Gadkar, D.G.; Gadkar, D.D.; Gajbhiye, S.A. A Review: Enhancement of turning process performance by effective utilization of hybrid nanofluid and MQL. *Mater. Today Proc.* **2021**, *38*, 44–47. [CrossRef]
2. Sivaiah, P.; Ajay Kumar, G.V.; Singh, M.M.; Kumar, H. Effect of novel hybrid texture tool on turning process performance in MQL machining of Inconel 718 superalloy. *Mater. Manuf. Process.* **2020**, *35*, 61–71. [CrossRef]
3. Pereira, O.; Rodríguez, A.; Fernández-Abia, A.I.; Barreiro, J.; De Lacalle, L.L. Cryogenic and minimum quantity lubrication for an eco-efficiency turning of AISI 304. *J. Clean. Prod.* **2016**, *139*, 440–449. [CrossRef]
4. Özbek, O.; Saruhan, H. The effect of vibration and cutting zone temperature on surface roughness and tool wear in eco-friendly MQL turning of AISI D2. *J. Mater. Res. Technol.* **2020**, *9*, 2762–2772. [CrossRef]
5. Davim, J.P.; Astakhov, V.P. Ecological machining: Near-dry machining. *Mach. Fundam. Recent Adv.* **2008**, 195–223.
6. Sultana, N.; Dhar, N.R. A critical review on the progress of MQL in machining hardened steels. *Adv. Mater. Process. Technol.* **2022**, *8*, 3834–3858. [CrossRef]
7. Patole, P.B.; Kulkarni, V.V.; Bhatwadekar, S.G. MQL Machining with nano fluid: A review. *Manuf. Rev.* **2021**, *8*, 13. [CrossRef]
8. Kim, H.J.; Seo, K.J.; Kang, K.H.; Kim, D.E. Nano-lubrication: A review. *Int. J. Precis. Eng. Manuf.* **2016**, *17*, 829–841. [CrossRef]
9. Altan Özbek, N.; Özbek, O.; Kara, F.; Saruhan, H. Effect of eco-friendly minimum quantity lubrication in hard machining of vanadis 10: A high strength steel. *Steel Res. Int.* **2022**, *93*, 2100587. [CrossRef]
10. Öndin, O.; Kıvak, T.; Sarıkaya, M.; Yıldırım, Ç.V. Investigation of the influence of MWCNTs mixed nanofluid on the machinability characteristics of PH 13-8 Mo stainless steel. *Tribol. Int.* **2020**, *148*, 106323. [CrossRef]
11. De Lacalle, L.L.; Angulo, C.; Lamikiz, A.; Sánchez, J.A. Experimental and numerical investigation of the effect of spray cutting fluids in high speed milling. *J. Mater. Process. Technol.* **2006**, *172*, 11–15. [CrossRef]
12. Vasu, V.; Pradeep Kumar Reddy, G. Effect of minimum quantity lubrication with Al_2O_3 nanoparticles on surface roughness, tool wear and temperature dissipation in machining Inconel 600 alloy. *Proc. Inst. Mech. Eng. Part N J. Nanoeng. Nanosyst.* **2011**, *225*, 3–16. [CrossRef]
13. Kazeem, R.A.; Fadare, D.A.; Ikumapayi, O.M.; Adediran, A.A.; Aliyu, S.J.; Akinlabi, S.A.; Akinlabi, E.T. Advances in the application of vegetable-oil-based cutting fluids to sustainable machining operations—A review. *Lubricants* **2022**, *10*, 69. [CrossRef]
14. TaeguTec-Cutting Tools Catalog. Available online: https://www.taegutec.com/pages/tr/publications/cutting-tools-catalogs/ (accessed on 8 November 2024).
15. Selvaraj, D.P.; Chandrasekar, P. Experimental investigations of nitrogen alloyed duplex stainless steel in dry milling process. *J. Eng. Sci. Technol.* **2018**, *13*, 321–331.
16. Li, Y.; Zheng, G.; Zhang, X.; Cheng, X.; Yang, X.; Xu, R. Cutting force, tool wear and surface roughness in high-speed milling of high-strength steel with coated tools. *J. Mech. Sci. Technol.* **2019**, *33*, 5393–5398. [CrossRef]
17. Badiger, P.V.; Desai, V.; Ramesh, M.R.; Prajwala, B.K.; Raveendra, K.J.M.R.E. Effect of cutting parameters on tool wear, cutting force and surface roughness in machining of MDN431 alloy using Al and Fe coated tools. *Mater. Res. Express* **2018**, *6*, 016401. [CrossRef]
18. Amigo, F.J.; Urbikain, G.; Pereira, O.; Fernández-Lucio, P.; Fernández-Valdivielso, A.; de Lacalle, L.L. Combination of high feed turning with cryogenic cooling on Haynes 263 and Inconel 718 superalloys. *J. Manuf. Process.* **2020**, *58*, 208–222. [CrossRef]
19. Yıldırım, Ç.V.; Sarıkaya, M.; Kıvak, T.; Şirin, Ş. The effect of addition of hBN nanoparticles to nanofluid-MQL on tool wear patterns, tool life, roughness and temperature in turning of Ni-based Inconel 625. *Tribol. Int.* **2019**, *134*, 443–456. [CrossRef]
20. Suryawanshi, S.R.; Pattiwar, J.T. Tribological performance of commercial Mobil grade lubricants operating with titanium dioxide nanoparticle additives. *Ind. Lubr. Tribol.* **2019**, *71*, 188–198. [CrossRef]
21. Fauzi, N.F.; Jaya, A.S.M.; Jarrah, M.I.; Akbar, H. Thin film roughness optimization in the TiN coatings using genetic algorithms. *J. Theor. Appl. Inf. Technol.* **2017**, *95*, 6690–6698.
22. Storchak, M.; Stehle, T.; Möhring, H.C. Determination of thermal material properties for the numerical simulation of cutting processes. *Int. J. Adv. Manuf. Technol.* **2021**, *118*, 1941–1956. [CrossRef]
23. Hao, G.; Liu, Z. The heat partition into cutting tool at tool-chip contact interface during cutting process: A review. *Int. J. Adv. Manuf. Technol.* **2020**, *108*, 393–411. [CrossRef]
24. Yıldırım, Ç.V.; Şirin, Ş.; Kıvak, T.; Sarıkaya, M. The effect of nanofluids reinforced with different surfactants on the machining and friction-wear properties of Waspaloy. *Tribol. Int.* **2023**, *181*, 108316. [CrossRef]
25. Özbek, O.; Altan Özbek, N.; Kara, F.; Saruhan, H. Effect of vibration and cutting zone temperature on surface topography during hybrid cooling/lubrication assisted machining of Vanadis 10. *Mater. Test.* **2023**, *65*, 1437–1452. [CrossRef]
26. Özbek, O. Evaluation of nano fluids with minimum quantity lubrication in turning of Ni-base superalloy UDIMET 720. *Lubricants* **2023**, *11*, 159. [CrossRef]
27. Kara, F. Experimental and Statistical Investigation of the Effect of Nanoparticle Minimum Quantity Lubrication (nano-MQL) Method on Cutting Performance. *Gazi J. Eng. Sci.* **2024**, *10*, 102–113. [CrossRef]
28. Arul, K.; Mohanavel, V.; Kumar, S.R.; Maridurai, T.; Kumar, K.M.; Ravichandran, M. Investigation of machining attributes on machining of alloys under nano fluid MQL environment: A review. *Mater. Today Proc.* **2022**, *59*, 1312–1318. [CrossRef]
29. Narasimha, M.; Tewodros, D.; Rejikumar, R. Improving wear resistance of cutting tool by coating. *IOSR J. Eng.* **2014**, *4*, 06–14. [CrossRef]

30. Gołombek, K.; Dobrzański, L.A. Hard and wear resistance coatings for cutting tools. *J. Achiev. Mater. Manuf. Eng.* **2007**, *24*, 107–110.
31. Akhtar, W.; Sun, J.; Sun, P.; Chen, W.; Saleem, Z. Tool wear mechanisms in the machining of nickel based super-alloys: A review. *Front. Mech. Eng.* **2014**, *9*, 106–119. [CrossRef]
32. Şirin, Ş.; Sarıkaya, M.; Yıldırım, Ç.V.; Kıvak, T. Machinability performance of nickel alloy X-750 with SiAlON ceramic cutting tool under dry, MQL and hBN mixed nanofluid-MQL. *Tribol. Int.* **2021**, *153*, 106673. [CrossRef]
33. Özbek, N.A.; Çiçek, A.; Gülesin, M.; Özbek, O. Investigation of the effects of cryogenic treatment applied at different holding times to cemented carbide inserts on tool wear. *Int. J. Mach. Tools Manuf.* **2014**, *86*, 34–43. [CrossRef]
34. Rahman Rashid, R.A.; Palanisamy, S.; Sun, S.; Dargusch, M.S. Tool wear mechanisms involved in crater formation on uncoated carbide tool when machining Ti_6Al_4V alloy. *Int. J. Adv. Manuf. Technol.* **2016**, *83*, 1457–1465. [CrossRef]
35. Gordon, S.; Phelan, P.; Lahiff, C. The effect of High Speed Machining on the Crater Wear Behaviour of PCBN Tools in Hard Turning. *Procedia Manuf.* **2019**, *38*, 1833–1848. [CrossRef]
36. Grigoriev, S.N.; Soe, T.N.; Hamdy, K.; Pristinskiy, Y.; Malakhinsky, A.; Makhadilov, I.; Solís Pinargote, N.W. The Influence of Surface Texturing of Ceramic and Superhard Cutting Tools on the Machining Process—A Review. *Materials* **2022**, *15*, 6945. [CrossRef] [PubMed]
37. Qadri, S.I.A.; Harmain, G.A.; Wani, M.F. Influence of tool tip temperature on crater wear of ceramic inserts during turning process of inconel-718 at varying hardness. *Tribol. Ind.* **2020**, *42*, 310. [CrossRef]
38. Trent, E.M.; Wright, P.K. Metal cutting operations and terminology. In *Metal Cutting*; Butterworth-Heinemann: Oxford, UK, 2000; pp. 9–20.
39. Rizzo, A.; Goel, S.; Luisa Grilli, M.; Iglesias, R.; Jaworska, L.; Lapkovskis, V.; Valerini, D. The critical raw materials in cutting tools for machining applications: A review. *Materials* **2020**, *13*, 1377. [CrossRef]
40. Gonzalez, H.; Pereira, O.; López de Lacalle, L.N.; Calleja, A.; Ayesta, I.; Muñoa, J. Flank-milling of integral blade rotors made in Ti_6Al_4V using Cryo CO_2 and minimum quantity lubrication. *J. Manuf. Sci. Eng.* **2021**, *143*, 091011. [CrossRef]
41. Laghari, R.A.; Jamil, M.; Laghari, A.A.; Khan, A.M.; Akhtar, S.S.; Mekid, S. A critical review on tool wear mechanism and surface integrity aspects of SiCp/Al MMCs during turning: Prospects and challenges. *Int. J. Adv. Manuf. Technol.* **2023**, *126*, 2825–2862. [CrossRef]